

Distributed Acoustic Sensing for detecting near surface hydroacoustic signals

Alexander S. Douglass,^{1,a} Shima Abadi,¹ and Bradley P. Lipovsky²

¹ *School of Oceanography, University of Washington, Seattle, WA 98195, USA; asd21@uw.edu, abadi@uw.edu*

² *Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA; bpl7@uw.edu*

Abstract

1 Distributed Acoustic Sensing (DAS) is a technology in which a fiber-optic cable is
2 turned into an acoustic sensor by measuring backscatter of light caused by changes in
3 strain from the surrounding acoustic field. In October 2022, 9 days of DAS and co-
4 located hydrophone data were collected in Puget Sound near Seattle, WA. Passive data
5 was continuously recorded for the duration and a broadband source was fired from
6 several locations and depths on the first and last days. This dataset provides direct
7 comparisons between DAS and hydrophone measurements, and demonstrates the
8 ability of DAS to measure acoustics signals up to ~500Hz.

9

10 Keywords: Distributed Acoustic Sensing, Submarine Fiber Optic Cable

^a Author to whom correspondence should be addressed.

11 **1. Introduction**

12 Acoustic monitoring is an important component of studying the wide variety
13 of sounds and sound sources in the ocean. Applications of ocean acoustics range from
14 general oceanography, studying of marine mammals, monitoring of natural and
15 anthropogenic ocean noise, defense, ocean exploration, and more. Unfortunately,
16 dense sampling of the acoustic field in large regions of the ocean can be impractical.
17 Deployment of large hydrophone arrays is challenging - the hydrophones may be
18 expensive and often require maintenance (which is particularly challenging for deeper
19 regions of the ocean), and denser sampling is only achieved by deploying more
20 hydrophones. Thus, alternatives that allow for increased coverage of the ocean at
21 reduced cost are highly desirable.

22 Distributed fiber optic sensing (DFOS) is a class of techniques in which a
23 fiber-optic cable, typically used for data transfer, acts as the sensor, capable of
24 measuring temperature (Distributed Temperature Sensing, DTS), strain (Distributed
25 Strain Sensing, DSS), or vibrations (Distributed Acoustic Sensing, DAS) (Bao and
26 Chen 2012). The use of fiber optic cables to measure acoustic waves (DAS) is a recent
27 development in this class of measurement techniques. DAS utilizes Rayleigh
28 backscattering of light from nano-scale defects in the fibers to measure acoustic waves
29 (Hartog, 2017; Masoudi and Newson 2015). An interrogator device attached to one
30 end of the cable sends repeated laser pulses through the cable and as these waves
31 interact with the fibers, phase changes in the scattered light over small sections of cable
32 (the gauge length) allow spatially resolved measurement of strain or strain-rate. These
33 strain and strain-rate measurements provide information about the average acoustic
34 field over the chosen gauge length, sampled at regular intervals along the cable. The

gauge length and sampling resolution are both parameters that can be varied depending on the application and limitations of the cable. The ranges over which the cables can be used to sense the acoustic field can be limited by several factors: the distance to the first repeater (if applicable), the attenuation along the fiber resulting in an SNR that is too low, or the sampling rate (such that each light pulse has enough time to travel to the desired point along the cable, and the backscattered light to propagate back to the interrogator, prior to the next pulse). Frequency capabilities are still an active area of exploration, but are known to extend to at least several hundred Hz (Taweessintananon et al. 2021, Lindsey and Martin 2021).

DAS was first explored as a technique for seismic applications and has received significant attention in that community over the last decade. The first demonstration of DAS was in 2009, using the technology as a replacement for borehole geophones, with additional similar field trials in 2010 (Mestayer et al. 2011). These initial field trials demonstrated the ability to do seismic imaging with DAS and produce comparable results to geophone-produced images in terms of signal-to-noise ratio and resolution. Additional demonstrations of DAS technology, capabilities, and applications followed over the next decade and it has become a significant area of research in seismology (Dou et al. 2017, Karrenbach et al 2018, Zhan et al. 2020, Lindsey et al. 2019, Sladen et al. 2019).

Recently, DAS has been explored as a means for measuring acoustic fields at frequencies above those typically relevant for seismic applications (>20 Hz). By extending DAS capabilities to higher frequencies, the technology can be utilized for measurements of acoustics in the water column. To date, only a small number of demonstrations of DAS for water column acoustics have been completed. DAS has

59 shown the ability to produce seismic images comparable to those generated by a typical
60 towed array method, particularly utilizing the lower spectral content of the seismic
61 source and when the offset range did not exceed the channel depth (Taweessintananon
62 et al. 2021, Matsumoto et al. 2021). Ship detection and tracking with signals up to 100
63 Hz has seen success in both shallow and deep water channels, with deeper water
64 performing better due to lower SNRs (Rivet et al. 2021). Finally, additional ship
65 tracking and detection of baleen whale calls below 100 Hz using a cable in the arctic
66 (Bouffaut et al. 2022, Landrø et al. 2021) and ship noise and fin whale calls (<20 Hz)
67 utilizing a cable from the Ocean Observatories Initiative (Wilcock et al. 2023) have
68 been demonstrated.

69 The focus of this manuscript is on an active-source experiment conducted in
70 the Puget Sound near Seattle, WA. The goal for this data is two-fold - to explore the
71 capabilities of DAS at frequencies up to 1 kHz, and to provide hydrophone
72 measurements taken close to the cable for direct comparison of the DAS
73 measurements. The remainder of this manuscript provides a detailed overview of the
74 experiment and a brief overview of some of the DAS measurements.

75

76 **2. DASCAL22 Experiment**

77 The DAS Calibration 2022 (DASCAL22) experiment took place in the
78 Saratoga Passage region of the Puget Sound in Washington State from October 19th,
79 2022 to October 28th, 2022. In this experiment, three hydrophones were deployed
80 adjacent to a fiber-optic DAS cable is buried in the seabed between Camano Island
81 and Whidbey Island. The water depth varies from 0 m (at the entry points to the water),
82 to a maximum of ~ 100 m, with the majority of the cable lying between ~ 80 -90 m

83 depth. The approximate location of the cable and the bathymetry along the cable are
84 shown in Figs 1a and 1b, respectively. A mooring with three hydrophones was
85 deployed next to the cable at ~93 m depth. Two hydrophones, a SQ26-H1B and a
86 CR1A (hydrophones A and B, respectively), were moored roughly 5 m from the sea
87 floor, and a third hydrophone, another CR1A (hydrophone C), was moored roughly
88 25 m from the sea floor (all hydrophones provided by Cetacean Research Technology,
89 Seattle, WA). The mooring location and layout are shown in Figures 1b and 1c,
90 respectively. The hydrophones all recorded ~9 days of passive acoustic data with 44.1
91 kHz sampling rates. During the mooring deployment and recovery days, an acoustic
92 source providing broadband impulsive signals was broadcast from three different
93 depths (1 m, 5 m, and 10 m) at 5 second intervals from various locations near the
94 mooring (with the boat's engine turned off during these broadcasts). The results
95 shown in this paper are from the data recorded on the recovery day (28 October, 2022)
96 when the current was weak, leading to a smaller variation in position during the
97 broadcasts.

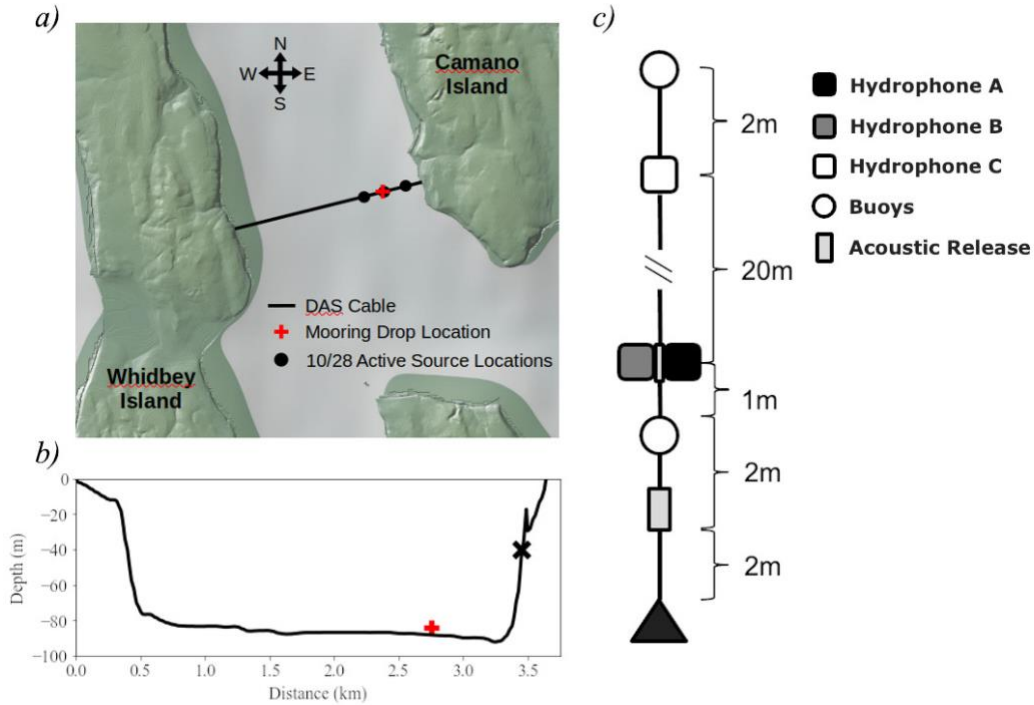
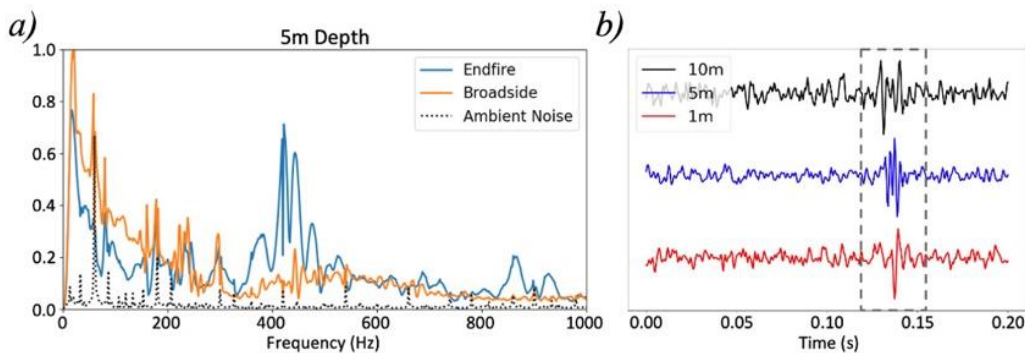


Fig. 1. DASCAL22 experimental setup. (a) The locations of the DAS cable, mooring, and active source testing, (b) the bathymetry along the DAS cable with the mooring location indicated by a red '+' and approximate location of the DAS channels considered in this study indicated by a black 'x'. (c) The mooring layout.

The acoustic source used during the experiment was a bubble pulser designed for geophysical surveys. The source consists of two electromechanical plates that are drawn together by applying a voltage to the plates, reversing direction after impacting, thus producing short-duration impulsive signals. In all broadcasts, the endfire dimension (along the face of the plates) was aligned parallel to the boat. On the equipment deployment day (19 Oct), a small reference hydrophone, an HTI-96-Min (High Tech, Inc., Long Beach, MS), was mounted 1 m from the center of the source to measure the signature from both broadside and endfire orientations at a 2 kHz sampling rate, allowing for characterization of the source signal measured by the

112 moored hydrophones and DAS cable. Figure 2a provides a normalized spectral
 113 average of 10 shots (per curve) at 5 m depth, at both endfire and broadside
 114 orientations, as well as an ambient noise curve for reference, taken using windows of
 115 data just prior to the shot recordings. A 15 Hz high pass filter is applied to all data, as
 116 well as a 1 Hz bandpass filter at 60, 180, 300, 420, 540, 660, 780, and 900 Hz,
 117 compensating for amplitude spikes caused by equipment noise at multiples of 60 Hz
 118 (this compensation is imperfect, and as a result, some sharp amplitude fluctuations are
 119 still visible at some of these frequencies). These plots show that the source provides a
 120 broadband signal with significant SNR across most of the frequency spectrum. Most
 121 notably, a significant amount of acoustic energy exists between ~ 350 -600 Hz in the
 122 endfire direction, and the broadside direction seems to provide a stronger signal at
 123 lower (<200 Hz) frequency ranges. Figure 2b shows a time domain measurement of
 124 three DAS channels (described next) with the source fired from three different depths
 125 and locations, demonstrating the capability of DAS to detect this source impulse. The
 126 Lloyd's mirror effect is noticeable in all three signals.



127
 128 Fig. 2. (a) Spectra of the bubble pulser measured by a hydrophone mounted
 129 approximately 1 m from the source center at endfire (blue) and broadside (orange)
 130 while at a 5 m depth. (b) Time domain measurements of the bubble pulser

131 broadcasting from three depths (1, 5, and 10 m) at DAS channels 427, 431, and 433,
132 respectively.

133 The submerged portion of the DAS cable is just over 3.5 km long, the full
134 length of which was sampled at a 2 kHz sampling rate. A gauge length of 6.38 m and
135 spatial resolution of 6.38 m were used. Though the water entry and exit points are
136 known exactly, the precise positions on the seafloor are not perfectly known and are
137 simply interpolated between these two points. DAS data was collected by Sintela Onyx
138 v1.0 interrogator.

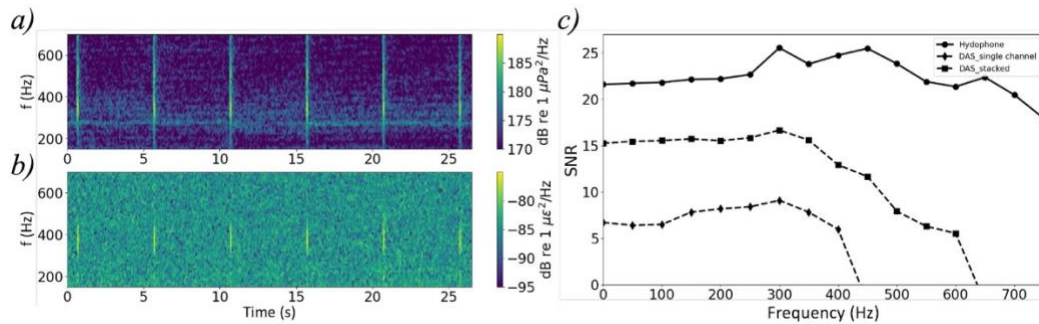
139 Over the 9 days between the equipment deployment and recovery, the three
140 moored hydrophones and DAS cable generated ~4 TB of data and measured the
141 acoustic field continuously, during which time there was significant boat traffic and a
142 variety of weather, including windy and rainy conditions. The focus of this paper is
143 only on the bubble pulser data recorded on the last day of deployment.

144

145 **3. Results & Discussion**

146 This data set provides an opportunity for direct comparison of DAS and
147 hydrophone measurements, and can be used for calibrating DAS outputs for proper
148 representation of ocean acoustic data. The goal for this manuscript, beyond the
149 introduction of this experiment and dataset, is to demonstrate that DAS is capable of
150 measuring an acoustic field at ranges >100 Hz. Figure 3 demonstrates one example of
151 such a recording. Six consecutive shots from the active source, broadcast on the
152 equipment recovery date (10/28), are plotted with data recorded by hydrophone A
153 (Figure 3a), showing a clear broadband signal with notable SNR. The output of a single

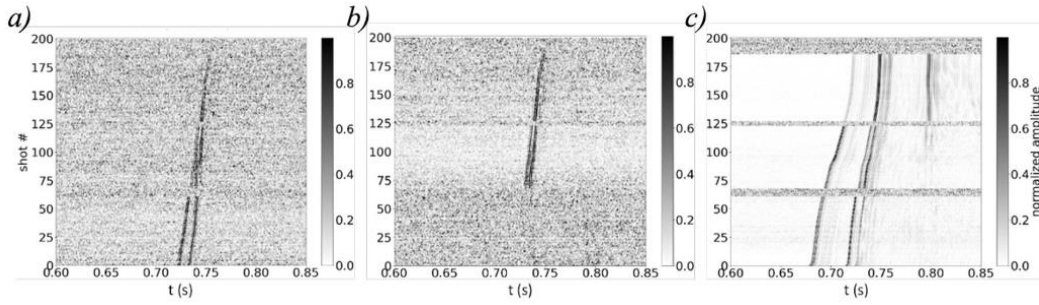
154 DAS channel (channel 431) over the same period of time also clearly shows
 155 measurements of six pulses, with notably lower SNR, but still clearly visible between
 156 ~ 300 -450 Hz (Figure 3b). The frequency response of a moving average with a period
 157 equal to the gauge length (6.38m) has frequency notches at ~ 235 Hz (speed of sound
 158 divided by gauge length) and ~ 470 Hz - notably the energy observed in these DAS
 159 signals are nicely within the bounds of these two notches. The Signal-to-Noise Ratio
 160 (SNR) for both hydrophone and DAS data is calculated from a 60 ms shot sample
 161 recorded at channel 431 and a 60 ms noise sample recorded 600 ms before the
 162 reception of the shot signal (Figure 3c). The SNR of the two measurements shows
 163 that the hydrophone measurements are significantly less noisy, but that significant
 164 improvements to the DAS SNR can be made by stacking 15 shots.



165
 166 Fig. 3. (a) Six consecutive shots of the bubble pulser at 5 m below the surface
 167 measured by hydrophone A and (b) channel 431 of the DAS cable. (c) The SNR of
 168 the pulses as measured by hydrophone A, DAS channel 431, and DAS channel 431
 169 with 15 shots stacked.

170 Figure 4 provides a waterfall plot of 200 consecutive time windows for two
 171 DAS channels (channel 427 in a, channel 431 in b) and hydrophone A (c), spanning
 172 ~ 20 minutes, at source depths of 10 m (shots 0-62), 5 m (shots 68-122), and 1 m (shots

128-186), with the source turned off during depth changes (evident in the waterfall plots), and the boat drifting with the current throughout the time window. During this time, the bathymetry at the source location varies from 66 m (starting) to 43 m (ending). The DAS measurements in both panels show a small time delay between two arrivals, corresponding to the direct path and surface reflection (note the delay shrinking when the source depth is decreased), as well as a slightly changing arrival time as the boat drifts further from the cable channels. The hydrophone shows similar characteristics, with time delayed surface reflections and a response slowly moving over time, as well as some multipath propagation. The first path corresponds to the direct path arrival, while the second is likely a path reflecting off of the sloped bathymetry, towards the hydrophone. The third path that arrives towards the top of the plot is likely due to a bathymetry change as the boat drifts, leading to a new, strong arrival. Note that the hydrophone is estimated to be ~ 750 m from the two DAS channels, thus the different impulse responses are expected. The two DAS channels shown here clearly pick up a direct path signal corresponding to the bubble pulser. The source is expected to be very close to these channels, thus a single strong arrival is expected. Additional arrivals, if they exist, may have lower SNRs that are undetectable, or propagate perpendicular to the cable where DAS has less sensitivity (Wilcock et al. 2023). Either of these may be the reason for a lack of signal detection in the first third of Figure 4b.



193

194 Fig. 4. Waterfall plots of ~ 200 shots of the bubble pulser for DAS channels (a) 427
 195 and (b) 431 at , and for (c) hydrophone A. All plots begin at $\sim 16:36:00$ UTC.

196 These results demonstrate the ability of DAS to record acoustic signals at
 197 frequencies >100 Hz, up to nearly 500 Hz without stacking and up to nearly 700 Hz
 198 with stacking. Some of the limitations of DAS are also highlighted in these results: the
 199 inability to detect broadside signals and the low SNR achievable relative to
 200 hydrophones both may impact the measurements shown here. While the
 201 measurement taken by the hydrophones has clear advantages, the DAS cable provides
 202 some advantages as well - particularly in the sampling density. While the SNR in a DAS
 203 channel is significantly lower, the abundance of channels provides the capability to
 204 coherently combine measurements to increase SNR, on top of the advantages
 205 discussed previously. This data provides multiple opportunities to explore and
 206 improve the understanding of DAS capabilities in ocean acoustics, such as improving
 207 SNR, applying standard array signal processing techniques to the data, extension of
 208 measurements up to 1 kHz, and consideration of other acoustic sources available in
 209 these measurements.

210

211 4. Conclusions

212 DAS technology is an exciting frontier in ocean acoustics, potentially
213 providing the ability to continuously monitor large regions of the ocean with dense
214 arrays. However, the technology is in its infancy and significant work exists to fully
215 exploit its capabilities. This experimental dataset provides a significant step towards
216 this goal, with co-located hydrophone and DAS measurements, allowing for direct
217 comparisons of the two measurements and calibration of signals recorded on DAS
218 cables. An overview of the DASCAL22 experiment was provided and several
219 conclusions from initial analysis of the data resulted.

220 First, it has been demonstrated that DAS technology is capable of detecting
221 acoustic signals up to approximately 700 Hz, and it is likely that the capabilities extend
222 to higher frequencies. Second, it is shown that the SNR of DAS cables is significantly
223 lower than that of traditional hydrophone recordings, which was expected, but that
224 some SNR can be recovered with clever combinations of measurements in the densely
225 sampled array. In these results, a difference of ~ 5 -15 dB SNR is seen, depending on
226 whether the channels are stacked or single measurements. However the DAS channels
227 used for this analysis are not co-located with the hydrophone, so this comparison is
228 not direct. Third, we see evidence of the impact of arrival angle on DAS channel
229 recordings, evidenced by the lack of multipath visible in DAS measurements shown
230 here.

231

232 **Acknowledgments**

233 We thank the crew of the R/V Weelander in the School of Oceanography at
234 the University of Washington. We also thank Dick Sylwester from the Northwest
235 Geophysical Services for generously lending us his bubble pulser to use in our study.

236 **References**

- 237 Bao, X. and Chen, L. (2012). “Recent Progress in Distributed Fiber Optic Sensors,”
238 Sensors **12**, 8601-8639.
- 239 Bouffaut, L., Taweessintananon, K., Kriesell, H. J., Rørstadbotnen, R. A., Potter, J. R.,
240 Landrø, M., Johansen, S. E., Brenne, J. K., Haukanes, A., Schjelderup, O., and
241 Storvik, F. (2022). “Eavesdropping at the Speed of Light: Distributed Acoustic
242 Sensing of Baleen Whales in the Arctic,” Front. Mar. Sci. **9**, 901348.
- 243 Daley, T. M., Freifeld, B. M., Ajo-Franklin, J., Dou, S., Pevzner, R., Shulakova, V.,
244 Kashikar, S., Miller, D. E., Goetz, J., Henningses, J., and Lueth, S. (2013). “Field
245 testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic
246 monitoring,” The Leading Edge **32**, 699-706.
- 247 Dou, S., Lindsey, N., Wagner, A. M., Daley, T. M., Freifeld, B., Robertson, M.,
248 Peterson, J., Ulrich, C., Martin, E. R., and Ajo-Franklin, J. B. (2017). “Distributed
249 Acoustic Sensing for Seismic Monitoring of The Near Surface: A Traffic-Noise
250 Interferometry Case Study,” Sci. Rep. **7**, 11620.
- 251 Hartog, A. H. (2017). An introduction to Distributed Optical Fibre Sensors (CRC
252 Press, Boca Raton, FL), p. 472.
- 253 Karrenbach, M., Cole, S., Ridge, A., Boone, K., Kahn, D., Rich, J., Silver, J., and
254 Langton, D. (2019). “Fiber-optic distributed acoustic sensing of microseismicity,
255 strain and temperature during hydraulic fracturing,” Geophysics **84**, D11-D23.

256 Landrø, M., Bouffaut, L., Kriesell, H. J., Potter, J. R., Rørstadbotnen, R. A.,
 257 Taweesintananon, K., Johansen, S. E., Brenne, J. K., Haukanes, A., Schjelderup,
 258 O., and Storvik, F. (2022). “Sensing whales, storms, ships and earthquakes using
 259 an Arctic fibre optic cable,” *Sci. Rep.* 12, 19226.

260 Lindsey, N. J., Dawe, T. C., and Ajo-Franklin, J. B. (2019). “Illuminating seafloor
 261 faults and ocean dynamics with dark fiber distributed acoustic sensing,” *Science*
 262 366(6469), 1103–1107.

263 Lindsey, N. J., and Martin, E. R. (2021). “Fiber-optic seismology,” *Annu. Rev. Earth*
 264 *Planet. Sci.* 49, 309–336.

265 Masoudi, A. and Newson, T. (2016). “Contributed Review: Distributed optical fibre
 266 dynamic strain sensing,” *Rev. Sci. Instrum.* **87**, 011501.

267 Matsumoto, H., Araki, E., Kimura, T., Fujie, G., Shiraishi, K., Tonegawa, T., Obana,
 268 K., Arai, R., Kaiho, Y., Nakamura, Y., Yokobiki, T., Kodaira, S., Takahashi, N.,
 269 Ellwood, R., Yartsev, V., and Karrenbach, M. (2021). “Detection of
 270 hydroacoustic signals on a fiber-optic submarine cable,” *Sci. Rep.* **11**, 2797

271 Mestayer, J., Cox, B., Wills, P., Kiyaschenko, D., Lopez, J., Costello, M., Bourne, S.,
 272 Ugueto, G., Lupton, R., Solano, G., Hill, D., and Lewis, A (2011). “Field Trials of
 273 Distributed Acoustic Sensing for Geophysical Monitoring,” *Society of*
 274 *Exploration Geophysicists*, 4253-4257.

275 Rivet, D., de Cacqueray, B., Sladen, A., Roques, A., and Calbris, G. (2021).
 276 “Preliminary assessment of ship detection and trajectory evaluation using
 277 distributed acoustic sensing on an optical fiber telecom cable,” *J. Acoust. Soc.*
 278 *Am.* **149**, 2615-2627.

279 Sladen, A., Rivet, D., Ampuero, J. P., De Barros, L., Hello, Y., Calbris, G., and
 280 Lamare, P. (2019). “Distributed sensing of earthquakes and ocean-solid Earth
 281 interactions on seafloor telecom cables,” *Nat. Commun.* 10(1), 5777.
 282 Taweesintananon, K., Landrø, M., Brenne, J. K., and Haukanes, A. (2021).
 283 “Distributed acoustic sensing for near-surface imaging using submarine
 284 telecommunication cable: A case study in the Trondheimsfjord, Norway,”
 285 *Geophysics* **86**, B303-B320.
 286 Wilcock, W. S. D., Abadi, S., and Lipovsky, B. (2023). “Distributed acoustic sensing
 287 recordings of low-frequency whale calls and ship noise offshore Central
 288 Oregon,” *JASA Express Lett.* **3** (2).
 289 Zhan, Z. (2019). “Distributed Acoustic Sensing Turns Fiber-Optic Cables into
 290 Sensitive Seismic Antennas,” *Seismol. Res. Lett.* **91**, 1-15.